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Transatlantic distribution of the Alaskan White River Ash.

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Transatlantic distribution of the Alaskan White River Ash

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ABSTRACT

Volcanic ash layers preserved within the geologic record represent precise time markers that correlate disparate depositional environments and enable the investigation of synchronous and/or asynchronous behaviors in Earth system and archaeological sciences. However, it is generally assumed that only exceptionally powerful events, such as supereruptions (≥450 km^3 of ejecta as dense-rock equivalent; recurrence interval of ~10^5 yr), distribute ash broadly enough to have an impact on human society, or allow us to address geologic, climatic, and cultural questions on an intercontinental scale. Here we use geochemical, age, and morphological evidence to show that the Alaskan White River Ash (eastern lobe; A.D. 833–850) correlates to the "AD860B" ash (A.D. 846–848) found in Greenland and northern Europe. These occurrences represent the distribution of an ash over 7000 km, linking marine, terrestrial, and ice-core records. Our results indicate that tephra from more moderate-size eruptions, with recurrence intervals of ~100 yr, can have substantially greater distributions than previously thought, with direct implications for volcanic dispersal studies, correlation of widely distributed proxy records, and volcanic hazard assessment.

INTRODUCTION

The geochemical correlation and dating of volcanic ash deposits defines the field of tephrostratigraphy (or tephrochronology), which has emerged as a powerful tool in geochronology because each individual ash deposit, or tephra, represents an isochronous stratigraphic horizon. Recent applications of tephrostratigraphy have illustrated the breadth of its applicability; it is a critical component in studies addressing African hominin genetic bottlenecks, Neanderthal extinction, and the asynchroneity of the Younger Dryas climate episode across the North Atlantic region (Lowe et al., 2012; Lane et al., 2013a, 2013b). Research spurred by the A.D. 2010 eruption of Eyjafjallajökull (Iceland) also illustrated how established tephrostratigraphic frameworks can help us understand the frequency of such costly events, aiding planning and prediction (Swindles et al., 2011). However, the full potential of tephrostratigraphy is only realized when a tephra is uniquely identifiable, preserved in a variety of depositional environments, and widely distributed. The use of tephra beds to correlate and date archaeological, geological, and paleoenvironmental archives on a regional scale is well established in Europe, western North America, Japan, and New Zealand, but there are no links between these regions. Only a single example of a tephra with a widespread intercontinental distribution is known: the supereruption of Toba (Indonesia) ca. 75 ka (Lane et al., 2013a). While it has been demonstrated that volumetrically smaller eruptions can distribute ash over vast distances (Zielinski et al., 1997), there is little evidence that they are preserved widely across the landscape.

Here we present the first recognition of a North American ash in Europe through the correlation of two tephras: the White River Ash in North America and the "AD860B" tephra in Europe. Each is an important regional stratigraphic marker in its own right (e.g., Lerbekmo, 2008; Lawson et al., 2012), and the knowledge that the two marker layers represent the same eruption has important implications in terms of tephra dispersal and tephrostratigraphy and its application to other disciplines.

The Bona-Churchill massif, a volcano in the Wrangell volcanic field of southeastern Alaska (Fig. 1) has had two major eruptions, separated by ~500 yr, in the past 2000 yr (Richter et al., 1995). Deposits from the eruptions are known as White River Ash north (WRAn), and east (WRAe) (Lerbekmo, 2008). WRAe is the volumetrically larger and younger event; a new wiggle-matched age of A.D. 833–850 has been determined for WRAe by multiple radiocarbon dates on tree rings from a spruce killed by the eruption (Table DR1 and Fig. DR1 in the GSA Data Repository[1]). It has a conservatively estimated eruptive volume of ~50 km^3 (23 km^3 dense-rock equivalent, DRE), which assigns it a magnitude of 6 on the volcanic explosivity index (VEI) (Lerbekmo, 2008). Put in perspective, this was an order of magnitude larger than the 1991 eruption of Mount Pinatubo (Philippines; Holasek et al., 1996), but approximately half the magnitude of the Mount Tambora (Indonesia) 1815 event (Self et al., 2004). WRAe remains a visible stratigraphic horizon ~1000 km east from the source (Fig. 1). The tephra is rhyolitic, with glass shards ranging in composition from ~72 to 75 SiO_2 wt% (normalized to 100% on a volatile-free basis). Visible deposits are mineral rich, predominantly plagioclase, amphibole, and Fe-Ti oxides, which commonly form microlites within glass shards. Glass morphology is typical for eruptive material from the Wrangell volcanoes, consisting largely of highly vesicular pumice (Fig. DR2). This eruption had a substantial impact on the indigenous peoples in the region, causing a major cultural changeover (Hare et al., 2004), and it is considered to

[1]GSA Data Repository item 2014311, information on source data for glass geochemistry compilations, supplementary figures including WRAe/AD860B images, geochemical plots, ^{14}C age model output, two tables of ^{14}C ages and glass geochemical means and standard deviations, and a dataset with all individual analyses, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

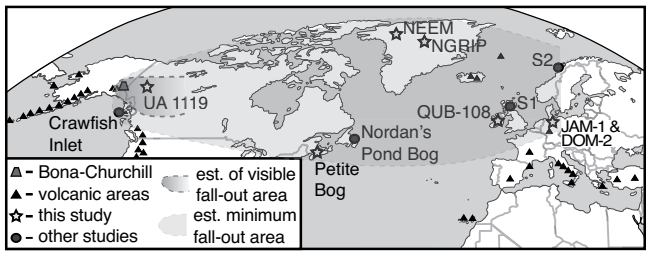

Figure 1. Site map showing locations of samples that were reanalyzed (stars), and several other previously published locales (circles): Crawfish Inlet (Alaska; Addison et al., 2010), Nordan's Pond Bog (Newfoundland; Pyne-O'Donnell et al., 2012), and sites S1 and S2, two examples of a more comprehensive list of sites in Europe from Lawson et al. (2012). Est.—estimate; NGRIP—North Greenland Ice Core Project; NEEM—North Greenland Eemian Ice Drilling; QUB—Queen's University Belfast; JAM—Jardelunder Moor; DOM—Dosenmoor. The lack of sites between proximal samples and eastern Canada reflects the absence of cryptotephra studies in this region.

be a likely cause for the southward migration of Athapaskan-speaking people to the American southwest (e.g., Mullen, 2012).

Tephrostratigraphy has played a major role in dating and correlating late Pleistocene to Holocene records across Europe. Much of this tephrostratigraphic framework is based on cryptotephra horizons (i.e., tephra deposits not visible to the naked eye; e.g., Pilcher et al., 1995; Swindles et al., 2011). The AD860B tephra was initially detected in Ireland and is among the first cryptotephras to be widely identified and geochemically characterized; its age of A.D. 776–887 (2σ) is based on multiple bounding radiocarbon dates on peat (Pilcher et al., 1996). It has since been found at sites across northern Europe, including Scotland, Norway, and Germany (Pilcher et al., 1995; van den Bogaard and Schmincke, 2002; Lawson et al., 2012), as well as in the North Greenland Ice Core Project (NGRIP) ice core (Coulter et al., 2012). However, the origin of this rhyolitic tephra has remained enigmatic. Most late-Holocene European cryptotephras have been traced to Icelandic sources (Haflidason et al., 2000), but AD860B has never been correlated to an Icelandic tephra, nor does it share any obvious characteristics with proximal Icelandic volcanic deposits that would allow speculation about a potential source (e.g., Wastegård et al., 2003; Lawson et al., 2012).

However, a comparison with data from sources farther afield shows that AD860B plots within the compositional field of Alaskan tephra from the Wrangell volcanic field (Figs. 2A and 2B). AD860B glass morphology is strikingly similar to that of WRAe, consisting of highly vesicular pumiceous glass shards with thin glass walls (Fig. DR2). Nearly identical age estimates, similar glass morphologies, and glass major element compositions prompted us to gather key AD860B samples for reanalysis by electron microprobe, alongside proximal reference material of WRAe. Samples from Sluggan Bog (Northern Ireland: sample QUB-108; Pilcher et al., 1995), Jardelunder Moor and Dosenmoor (Germany: samples JAM-1, DOM-2; van den Bogaard and Schmincke, 2002), and the NGRIP ice core (Greenland: sample QUB-1528; Coulter et al., 2012), were reanalyzed with UA 1119, a WRAe sample collected along the axis of the plume in central Yukon, Canada. Two new samples with the same age and morphology as WRAe from Petite Bog (Nova Scotia), and Greenland (North Greenland Eemian Ice Drilling, NEEM-2011-S1 core) were also included (Fig. 1). New analyses were considered essential because previously published data were collected over ~20 yr, with different instruments, analytical conditions, and standards. In addition, the standard oxide suite (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K) was expanded to include Cl, which is absent in most previous analyses but abundant in WRAe in comparison to available Icelandic glass analyses.

METHODS

Major and minor element geochemical analyses were performed on single glass shards and were carried out at the University of Alberta on a Cameca SX100 using a 5 µm beam and 3 nA current, and a JEOL 8900 using a 10 µm beam and 6 nA current. The Petite Bog sample was analyzed at the University of Edinburgh, and QUB-1830 (NEEM-2011-S1) was analyzed at Queen's University Belfast. Details on analytical methods are available elsewhere (Jensen et al., 2008; Coulter et al., 2012; Pyne-O'Donnell et al., 2012).

All samples were analyzed concurrently with secondary standard ID3506 (a Lipari obsidian), as well as Old Crow tephra, at the University

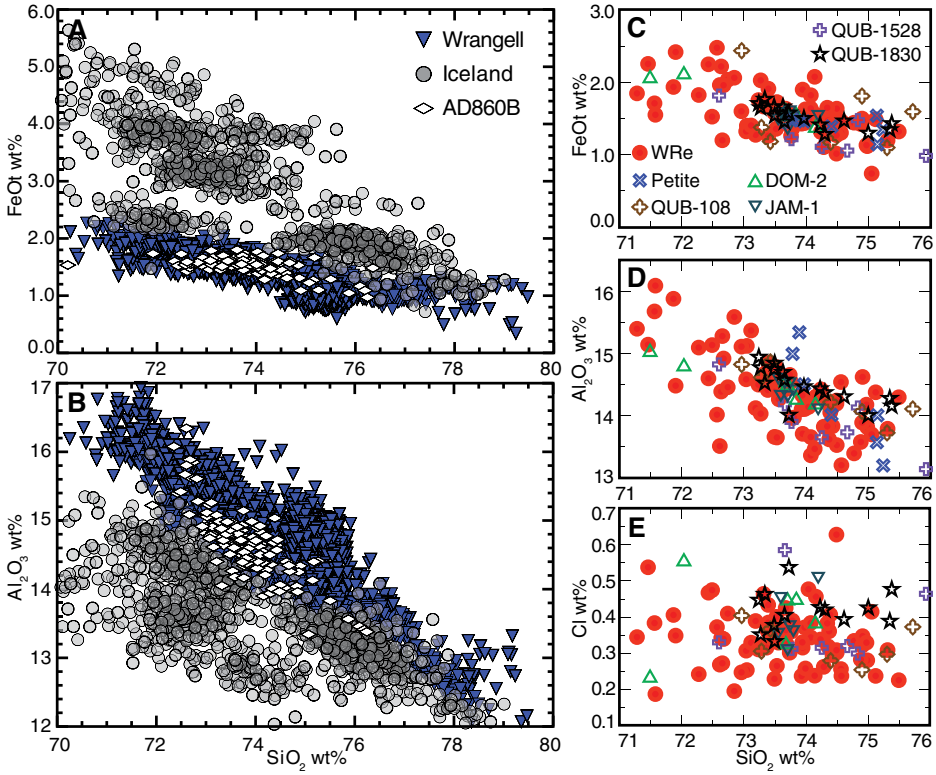

Figure 2. Harker diagrams illustrating the glass major element geochemistry of Icelandic and Wrangell (Alaska) tephra, and new "AD860B" and White River Ash east (WRAe) glass data (normalized). A, B: Initial examination of published AD860B data (www.Tephrabase.org, and references therein; Pilcher et al., 1995; van den Bogaard and Schmincke, 2002) plotted with Icelandic and Wrangell tephra shows the clear affinity of AD860B with Wrangell tephra. C–E: New analyses of UA 1119 (WRAe reference sample) plotted with reanalyzed AD860B samples, Petite Bog (Nova Scotia), and North Greenland Eemian Ice Drilling core NEEM-2011-S1 (sample QUB-1830), show that all samples plot within the geochemical range of WRAe. Samples also tend to cluster between ~73 and 74.5 SiO_2 wt%, the most abundant population within WRAe. Cl values are similar for all samples, an important result because WRAe glass has higher concentrations of Cl relative to glass in Icelandic tephra. Additional diagrams are available in Figure DR3 (see footnote 1).

of Alberta and with ATho reference glass at Queen's University Belfast. Secondary standards were analyzed at the start and end of each run, and after ~75–100 individual analyses, to assess the quality of calibration. All samples, excepting QUB-1830, were analyzed concurrently with WRAe reference sample UA 1119, and were reanalyzed from previously produced mounts (Pilcher et al., 1995; van den Bogaard and Schmincke, 2002; Coulter et al., 2012). Standard analyses and results are available in Tables DR2 and DR3. All data presented are normalized to 100% on a volatile-free basis.

High-resolution trace chemical and elemental analyses of the NEEM-2011-S1 ice core, as well as reanalyses of archived NGRIP samples, were carried out at the Desert Research Institute (Nevada, USA) using a continuous ice core melter coupled to two inductively coupled plasma mass spectrometers and a range of other instruments (Sigl et al., 2013). For NGRIP particle analysis, an Abakus® (Klotz, Germany) laser-based particle counter also was included in the analytical system to measure semiquantitatively particle concentrations for various size ranges (Ruth et al., 2003), although glass shards were initially located by centrifuging meltwater and mounting individual samples onto slides for examination by light microscope. Particle volume was estimated from the size and count number assuming spherical shape of the individual particles, and mass was estimated from the volume assuming a density of 2.65 g/cm^3.

RESULTS AND DISCUSSION

Our results show that AD860B and WRAe have indistinguishable glass major element geochemistry (Fig. 2; Fig. DR3). These results, taken together with their coincident ages and identical glass-shard morphology, collectively demonstrate that they are most likely the product of the same eruption. The recently determined Greenland Ice Core Chronology 2005 (GICC05; see Vinther et al., 2006) age of A.D. 846–848 for AD860B (Coulter et al., 2012) is considered the most precise age available for the tephra, with the newly determined WRAe radiocarbon age of A.D. 833–850 providing a precise age independent of the ice core chronology. This correlation, and the identification of WRAe in the northeast Pacific Ocean (Addison et al., 2010) and eastern Newfoundland (Pyne-O'Donnell et al., 2012), indicates that WRAe and AD860B form a single isochron that extends from the Pacific Ocean, across North America and Greenland, and into northern Europe, a distance of at least 7000 km (Fig. 1). The presence of the tephra in Nova Scotia, in addition to Newfoundland, suggests that it will be an important marker for sites across Canada and the northeast United States.

The presence of the tephra in Greenland and Europe enables us to examine the extraregional impact of the eruption. Timing of the eruption is revealed by the presence of large particles in NGRIP ice that indicate that the tephra arrived in Greenland between July and December A.D. 847 ± 1 (GICC05) (Fig. 3A). This timing is consistent with prevailing wind directions in the interior of Alaska that have southwesterly and westerly winds becoming predominant in July, before reverting to more northerly and easterly directions in January (Muhs and Budahn, 2006). Chemical records from NGRIP and NEEM-2011-S1 cores show an increase in chlorine deposition coincident with particle and acid deposition, but only a modest increase in sulfate, with deposition appearing to be slightly delayed and more evident in the northern NEEM site (estimated deposition of 20.6 ± 3.9 kg km^{-2}; Sigl et al., 2013) (Figs. 3B and 3C). The spatial heterogeneity in deposition of the sulfate highlights a key limitation of ice core sulfate records, which are often used to assess the frequency of past volcanic eruptions (e.g., Bigler et al., 2002).

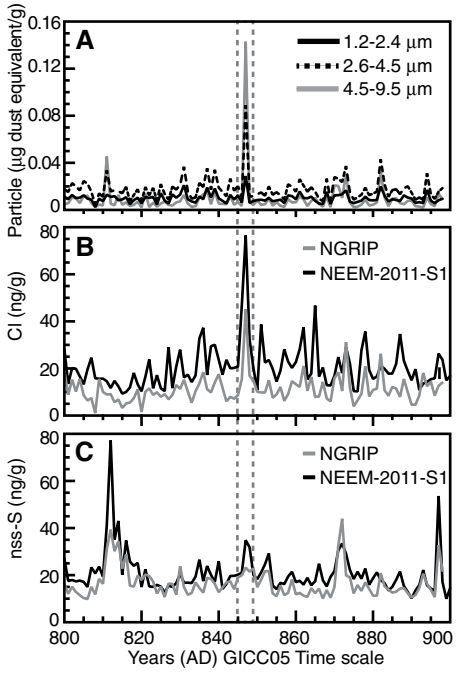

Figure 3. Particulate, Cl, and S data from the North Greenland Ice Core Project (NGRIP) and North Greenland Eemian Ice Drilling sample NEEM-2011-S1. A: White River Ash east (WRAe)/AD860B form a distinct peak in the particulate data from NGRIP, showing that continuous flow particle counting can assist in pinpointing the location of tephra within an ice core. The largest diameter measured was 9.5 μm, which corresponds to the highest peak, differentiating it from nonvolcanic dust deposited on the Greenland Ice Sheet that rarely has a mean diameter of >2 μm (e.g., Ruth et al., 2003). B: HCl dominates the acidity loading. C: Volcanic H_2SO_4 deposition was low and limited to the NEEM-2011-S1 site (nss—non-sea salt). The rise in H_2SO_4 is slightly delayed compared to Cl, although both peak at similar times. All data are presented on the Greenland Ice Core Chronology 2005 (GICC05) time scale (Vinther et al., 2006).

The short-lived sulfate peaks and relatively low aerosol loading indicate that WRAe/AD860B was unlikely to have had an appreciable impact on climate. Decadally resolved peat records in Ireland reveal that the eruption occurred at a time of already deteriorating (i.e., wetter and/or colder) climate conditions, yet an intensification of agriculture can be observed in numerous pollen records in the period immediately following the event (Kerr et al., 2009). Thus, available paleoenvironmental data suggest that the eruption did not have a significant environmental impact beyond the immediate region affected by major ash fall. Nevertheless, the tephra provides a valuable isochron for future studies to assess the synchroneity of environmental change around that time, such as the onset of the Medieval Climatic Anomaly (ca. A.D. 900–1300) on either side of the Atlantic Ocean.

Notwithstanding the lack of evidence for any widespread climate impact, the distribution of WRAe across the northern middle to high latitudes, covering one-third of the globe's circumference at ~lat 60ºN, has important implications for volcanic hazard assessments. The A.D. 2010 eruption of Eyjafjallajökull provided an excellent example of how even modest eruptions (VEI 4) can produce ash plumes that substantially impact human activities (Mazzocchi et al., 2010; Stevenson et al., 2012). The eruption caused the incremental closure of airspace over Europe for more than a week, grounding over 100,000 flights and 10 million passengers, while costing the European aviation industry approximately U.S. $3.3 billion (Mazzocchi et al., 2010). Ash from the event was unevenly distributed across Europe, with an average mass loading of 8–218 shards cm^2, and a shard size distribution of 20–50 μm (Stevenson et al., 2012). Many cryptotephra from European geologic records have size distributions and/or shard densities within, or above, this range, suggesting that past events would have had a similar, if not greater, impact (Swindles et al., 2011; Stevenson et al., 2012). Thus, the modern-day consequences of a WRAe-like plume extending across North America, the North Atlantic, and into northwest Europe would be enormous. Increased knowledge of tephra distribution from large prehistoric eruptions, combined with recent studies, is crucial for evaluating volcanic hazards and formulating mitigation strategies (Mazzocchi et al., 2010; Swindles et al., 2011).

The intercontinental correlation of volcanic ash presented here, together with rapidly maturing capabilities for characterizing and correlating cryptotephra, highlights the need to consider extremely distal source volcanoes for unknown cryptotephra deposits. It seems plausible that the lack of other intercontinental correla-

tions does not result from the rarity of exceptional events (e.g., the Toba event), but perhaps because uncorrelated tephras are often attributed to uncharacterized eruptions from typical local source volcanoes. Several Holocene eruptions of similar or greater magnitude, such as Aniakchak (Alaska) and Mount Mazama (Oregon), have been documented in Greenland ice cores (Zdanowicz et al., 1999; Pearce et al., 2004) and in Newfoundland (Pyne-O'Donnell et al., 2012), and would be excellent candidates for detection in European sequences.

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Transatlantic distribution of the Alaskan White River Ash

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